THRUST CHAMBER LIFE PREDICTION

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Abstract

The reusable life of the Space Shuttle Main Engine (SSME) is influenced by the cyclic life of the regeneratively liquid cooled main combustion chamber (MCC). During an operational duty cycle the MCC liner is subjected to a large transient thermal gradient that imparts a high thermal cyclic strain to the liner hot gas wall. Life predictions of such chambers have usually been based on low cycle fatigue (LCF) evaluations. Hot-fire testing, however, has shown significant mid-channel wall deformation and thinning during accrued cyclic testing. This phenomenon is termed cyclic creep and appears to be significantly accelerated at elevated temperatures.

An analytical method that models the cyclic creep phenomenon and its application to thrust chamber life prediction is presented. The chamber finite element geometry is updated periodically to account for accrued wall thinning and distortion. Failure is based on the tensile instability failure criterion. Cyclic life results for several chamber life enhancing coolant channel designs are compared to the typically used LCF analysis that neglects cyclic creep. The results show that the usable cyclic creep life is approximately 30 to 50% of the commonly used LCF life.

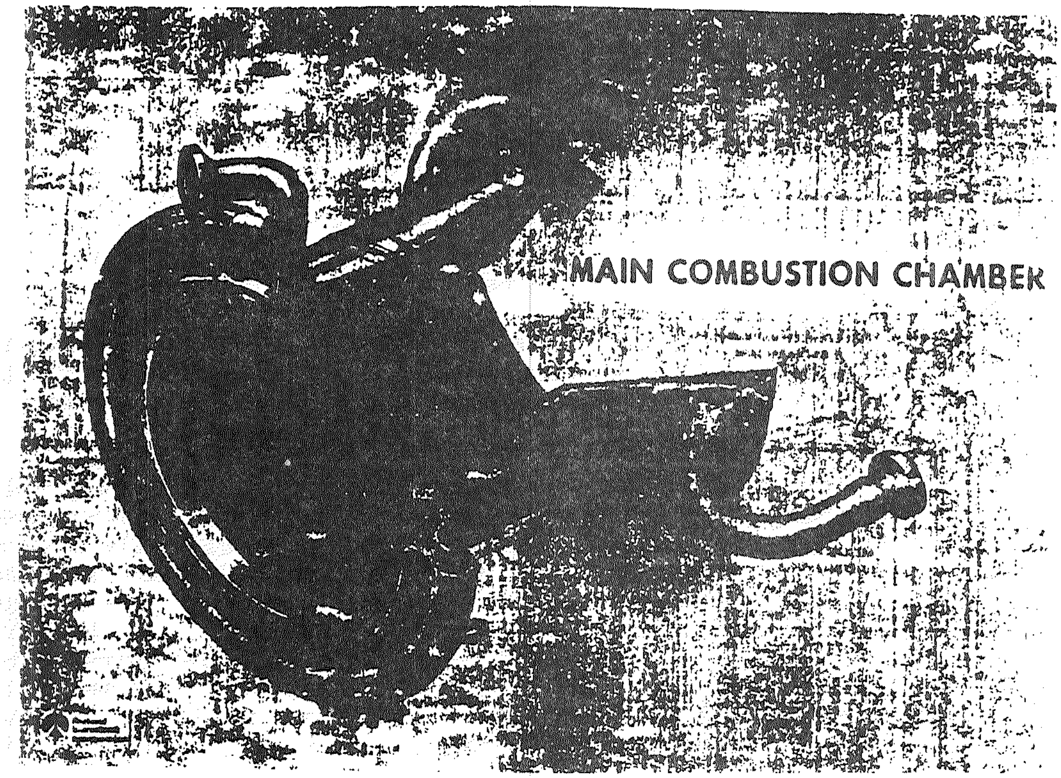
Introduction

The reusable life of the Space Shuttle Main Engine (SSME) and future engines are greatly influenced by the cyclic life of several major components subjected to high temperature environments. The main combustion chamber (MCC) liner is exposed to an environment that produces a heat flux of approximately 100 BTU/in^2-sec in the life limited throat region. To accommodate this high heat flux, the copper base MCC liner is regeneratively cooled through integral rectangular cooling channels. During operational duty cycles (missions) the MCC liner hot gas wall experiences large thermal plastic cyclic strains resulting from a large transient thermal gradient. These cyclic strains influence the fatigue life of the MCC liner hot gas wall.

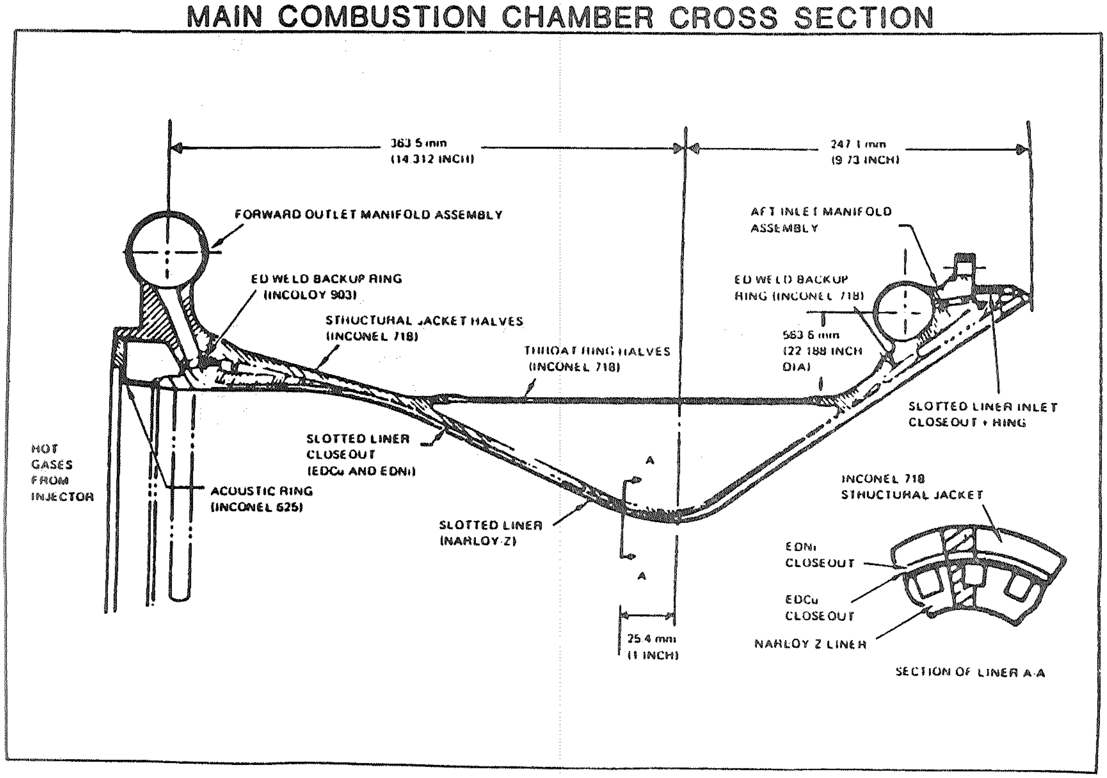
Low cycle fatigue life is typically a function of the cyclic strain range, the material properties and the operating temperature. The theoretical reusable life is normally determined by the number of strain cycles that can be accrued before initiation of surface cracks. Hot-fire testing of channel wall combustors at Rocketdyne and NASA Lewis Research Center (LeRC), however, indicates that fatigue is not necessarily the dominate failure mode. Significant mid-channel permanent deformation and wall thinning is witnessed during these hot-fire tests. It is concluded that the failure mode is one of strength once the wall has thinned to its critical thickness. The thinning phenomenon is termed cyclic creep and appears to be significantly accelerated at elevated temperatures. The sensitivity of the phenomenon to surface temperature is evidenced by the non-uniformity of channel wall deformation around the circumference of the combustors.

In 1973, work began at LeRC to systematically investigate the problem of thrust chamber life. The approach was to use cyclic testing under controlled conditions, and with a test procedure specifically designed to study thrust chamber life, finite element analyses were performed to compute strain range. Attempts were made to predict life assuming low cycle thermal fatigue failure mechanics and using life data from universal isothermal laboratory fatigue tests as a reference. This life prediction procedure was generally unsuccessful. Consequently, it was decided that an analytical method that models the observed cyclic creep phenomenon was needed to improve life prediction capability.

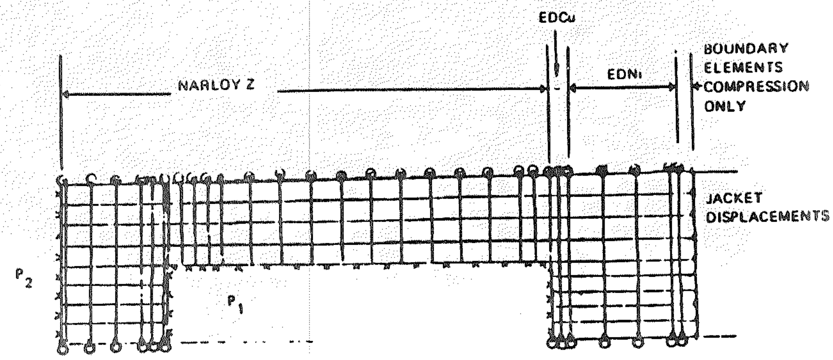
An analytical method was developed that periodically updates the chamber finite element geometry to account for accrued wall thinning and distortion. The methodology consists of analyzing the chamber considering more increments in the duty cycle and geometric deformation effects. The geometric deformation formulation allows the analysis to adjust to small geometry changes that occur during each duty cycle and are cumulative in nature. In order to minimize computer time, an extrapolation procedure is utilized. To perform the analysis, five duty cycles are sequentially analyzed and the change in geometric shape is extrapolated to the deformation conditions 15 cycles futher on, e.g., 5 cycles + 15 cycles = 20 cycle condition. Using the new geometry, additional duty cycles are analyzed and another extrapolated shape projection made. This technique is continued until failure occurs. Failure is based on the tensile instability failure criterion. Cyclic creep life analysis results for several chamber life enhancing designs, when compared to the typically used low cycle fatigue (LCF) analysis results, show that the usable cyclic creep life is approximately 30 to 50% of the LCF life.



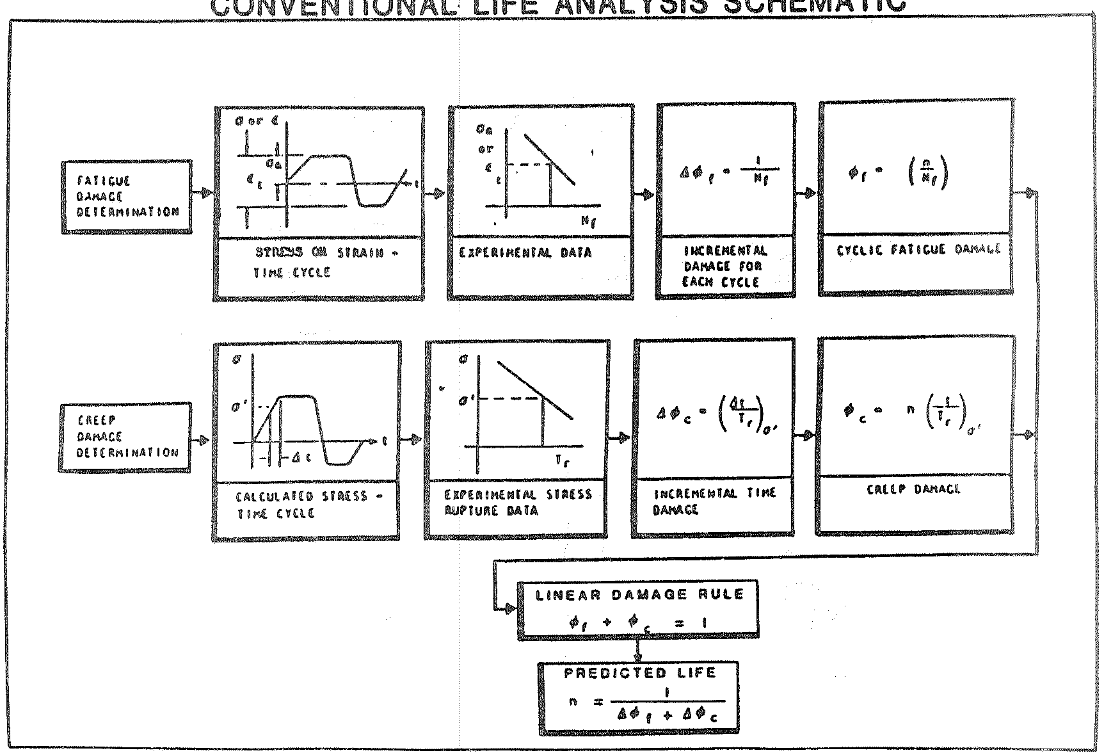
MAIN COMBUSTION CHAMBER CROSS SECTION

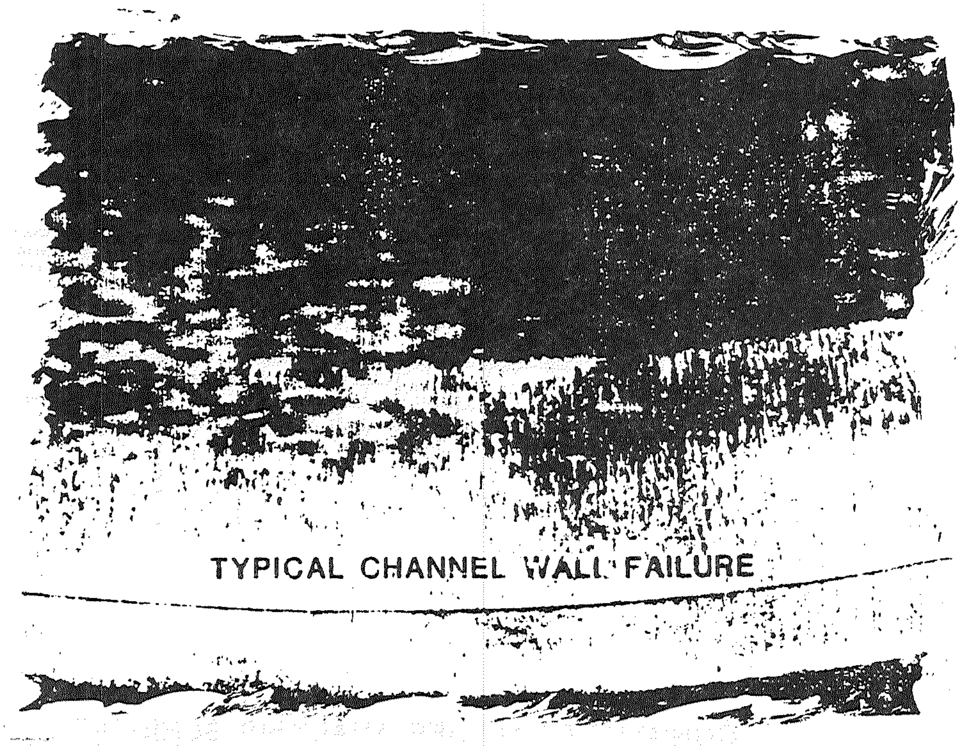


STRUCTURAL ANALYSIS MODEL



CONVENTIONAL LIFE ANALYSIS SCHEMATIC

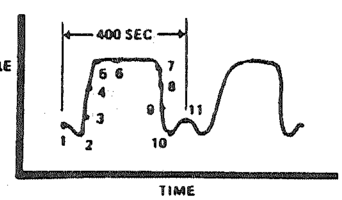




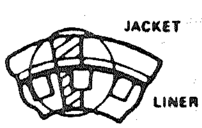
TYPICAL CHANNEL WALL FAILURE

CYCLIC CREEP
LIFE ANALYSIS APPROACH

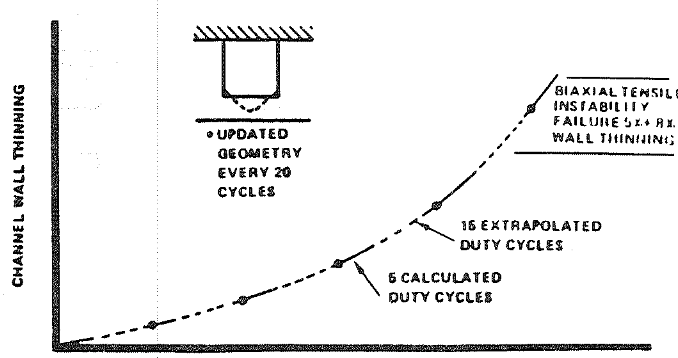
- CONSIDER
  - TEMPERATURE AND PRESSURE HISTORY
  - JACKET RADIAL DISPLACEMENTS AND AXIAL RESTRAINT
  - INITIAL RADIAL LINER GAP 0.508 mm (0.020 IN.)
  - STRUCTURAL MODEL
    - PLANE STRAIN CROSS SECTION
    - INELASTIC MATERIAL – KINEMATIC HARDENING
    - GEOMETRIC DISTORTIONS
    - CREEP/RELAXATION



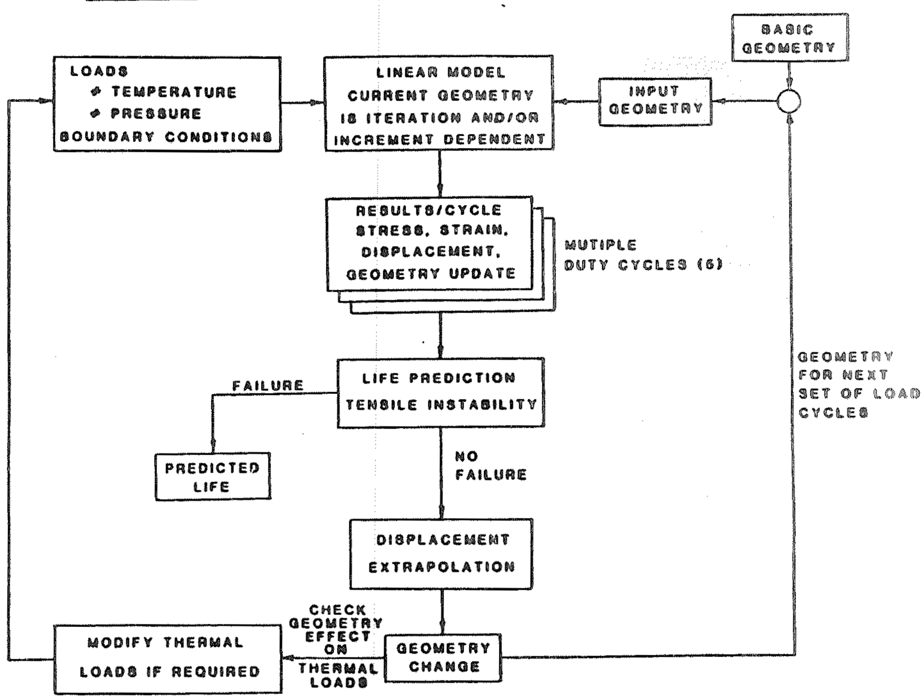
DUTY CYCLE, ~ 11 INCREMENTS



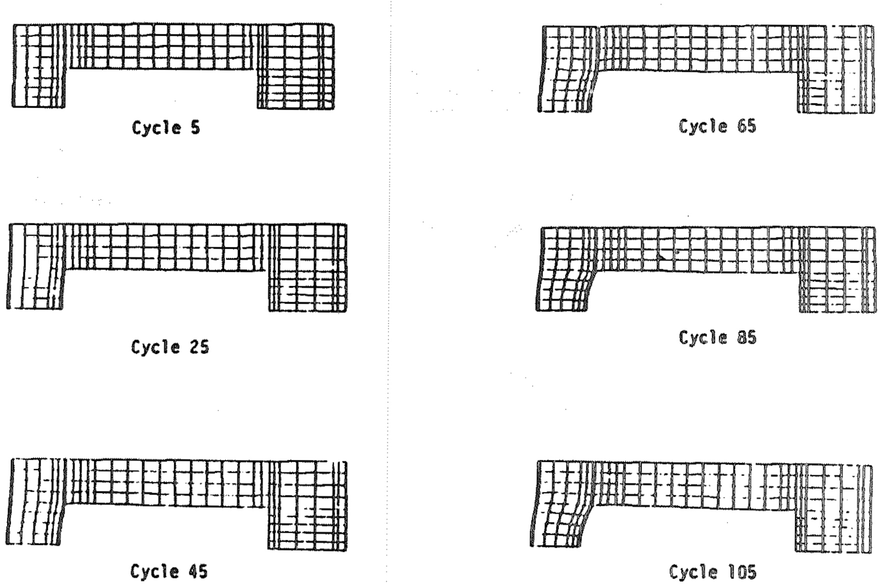
THERMAL/STRUCTURAL MODEL



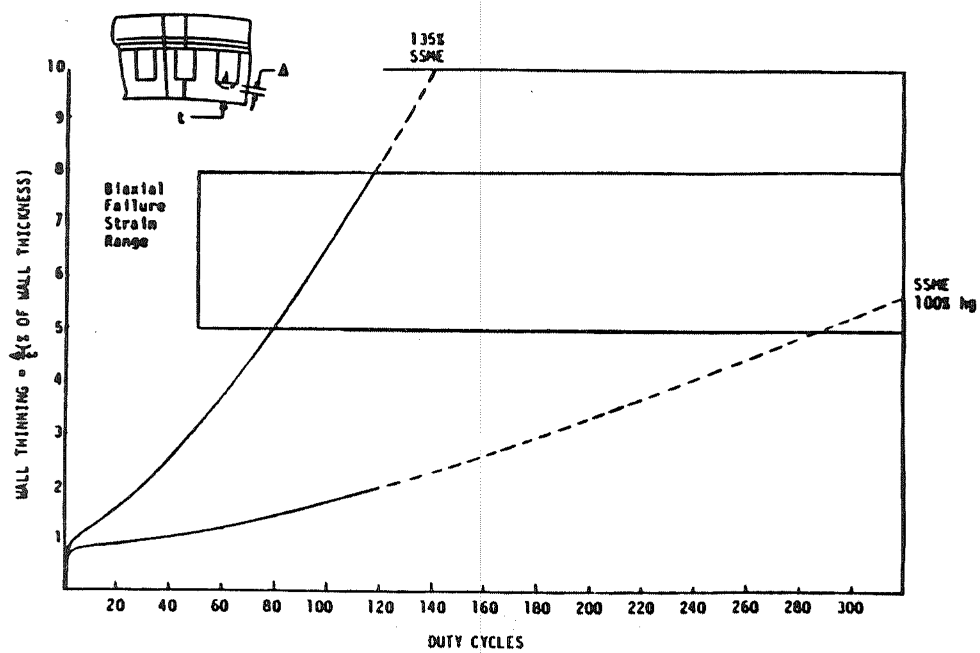
CYCLIC CREEP LIFE ANALYSIS SCHEMATIC



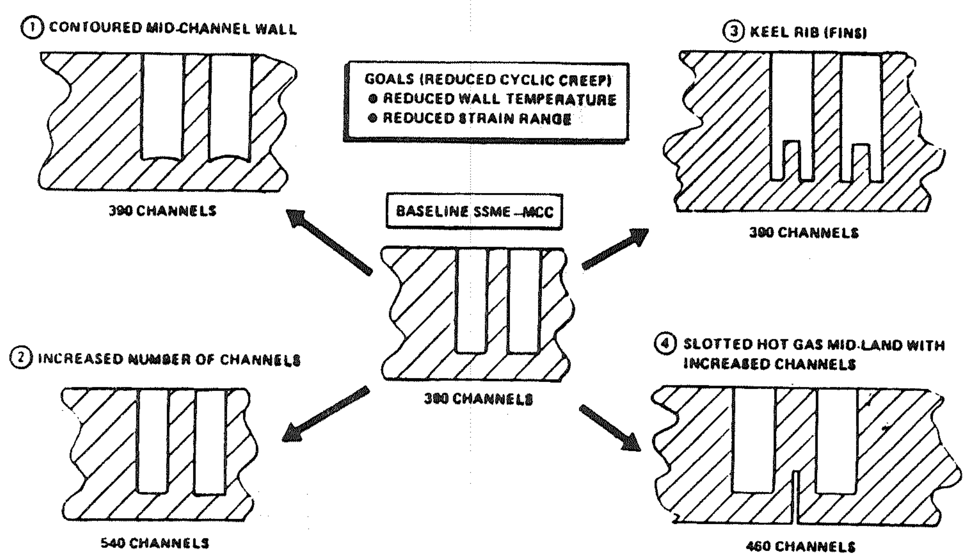
TYPICAL GEOMETRIC SHAPE CHANGE WITH CYCLING



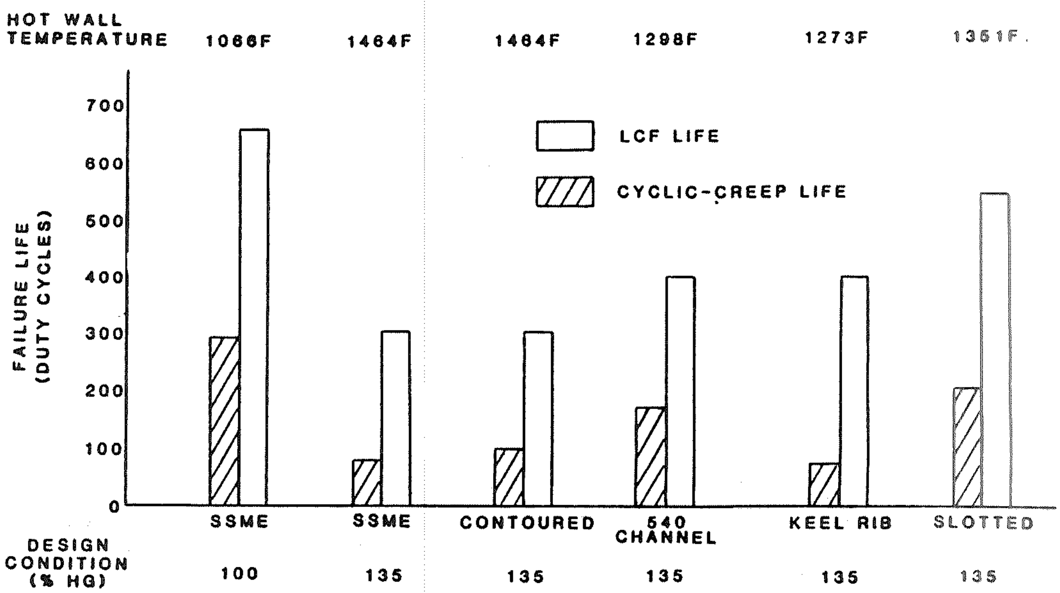
MID-CHANNEL WALL PERMANENT DEFORMATION (THINNING)



LIFE ENHANCED DESIGNS



COMPARISON OF LIFE ENHANCED DESIGNS



SUMMARY

- Analytical model provides, a refined analysis that models the observed failure mode

- Predicted cyclic-creep life is typically 30 to 50% of the low-cycle-fatigue life

- The most feasible approach to increasing SSME-MCC life is increasing the number of coolant channels